LEVEL II

USAFETAC/TN-81/001

SOIL MOISTURE AND AGROMET MODELS

Technical note

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Two automated models, known as Soil Moisture and Agromet, used operationally to monitor crop growing conditions are described. The Soil Moisture model uses Thornthwaite's water balance method to estimate moisture parameters from daily temperature and precipitation analyses. The model is relatively simple, and it has been providing useful information for over 20 years. The newer and more complex Agromet model estimates daily evaporation potential using Penman's equation. This model also uses a complex cloud analysis to estimate (Cont'd)

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20. ABSTRACT (Cont'd)

radiation effects. Agromet provides daily grid-point analyses of temperature, precipitation, snow depth, radiation, and evaporation.

PREFACE

This technical note provides a current description of USAFETAC Soil Moisture and Agromet programs. Changes in these programs over the past two years have left the previous report, USAFETAC TN 77-3, outdated in many of its particulars. While I have relied on TN 77-3, I have not merely patched up the previous report. The material has been updated, expanded, and reorganized. For each program, user products are described first and followed by sections on the general methods, the calculations, and lastly, the production programs. This way, the reader does not have to progress through the details of how the programs work to find out what they do. But I hope someone will want to.

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INTRODUCTION

The USAF Environmental Technical Applications Center (USAFETAC) prepares meteorological analyses tailored for use by government agencies to monitor crop growing conditions over much of eastern Europe, Asia, and the United States. USAFETAC's support to these customers is provided under two projects, known as "Soil Moisture" and "Agromet."

The Soil Moisture program has been active since 1958. It uses C. W. Thornthwaite's method (Thornthwaite and Mather, 1957) to compute water balance. Thornthwaite's method requires only precipitation and temperature data as routine input--elements readily available from surface observations. The approach is simple, and it has been providing useful information for over 20 years.

The Agromet program became operational in 1974. It was developed as interest in worldwide crop production grew in the early 1970s and data became available at the Air Force Global Weather Central (AFGWC) to meet the requirements of a more complex model. Among its advances over the Soil Moisture program, the Agromet program uses AFGWC's Automated Cloud Analysis Model (3DNEPH) to estimate the effect of clouds on the radiation balance and uses Penman's (1956) evaporation formula.

The models, procedures, and products are described in Chapters 1 (Soil Moisture) and 2 (Agromet). Some basic terms are defined in the Glossary.

Chapter 1

SOIL MOISTURE PROGRAM

1.1 Automated Products

The Soil Moisture program produces daily temperature and preciptation analyses and 10-day ("decade") soil moisture estimates. The decade programs update the water balance as of the 10th, 20th, and last day of each month. The third and final decade of each month also produces monthly summaries.

The Soil Moisture program covers two geographical areas. Area 1, the "European" or "Soviet" area, is bounded roughly by 45°N-60°N and 10°E-100°E. Area 2, the "Asian" or "China" area runs from 10°N to 50°N and from 100°E to the east coast of the continent. Computer analyses are done on the 1/3-mesh grid (grid distance 1/3 of AFGWC full mesh, approximately 60 NM) on a 1:15,000,000 polar stereographic map. The areas covered are shown in Figures 1-1 and 1-2.

In addition to the grid point maps, the decade run produces area averages in tabular form. These tables list decade and monthly temperatures, precipitation, and departures from long-term means for 35 regions in Area 1 and for 23 regions in Area 2. For Area 1, the "simple aggregate means" are simply the total of the grid point values divided by the number of grid points in the region. In Area 2, due to local variations of soil, terrain, or climate, there are often sparsely sown and heavily cultivated areas within a region. To better reflect conditions over sown acreage, grid-point values are weighted according to agricultural land use to produce weighted means and departures in Area 2. A complete list of the Soil Moisture programs' maps and charts follows:

a. Daily Maps.

(1) Maximum Temperature (°C)

(2) Minimum Temperature (°C)

(3) 24-Hour Precipitation (mm)

b. Decade Maps.

(1) Days in Decade when Mean Values Used for Missing Temperatures

(2) Days in Decade when Mean Values Used for Missing Precipitation

(3) Mean Temperature (tenths of °C)

(4) Decade Total Precipitation (mm)

(5) Soil Moisture (mm)

(6) Ratio: Actual Evapotranspiration/Potential Evapotranspiration

(7) Moisture Surplus (mm)

(8) Tractionability (Thornthwaite Indices)

(9) Decade Departure from Mean Temperature (tenths of °C)

(10) Decade Percent of Mean Precipitation

(11) Percent of Mean Soil Moisture

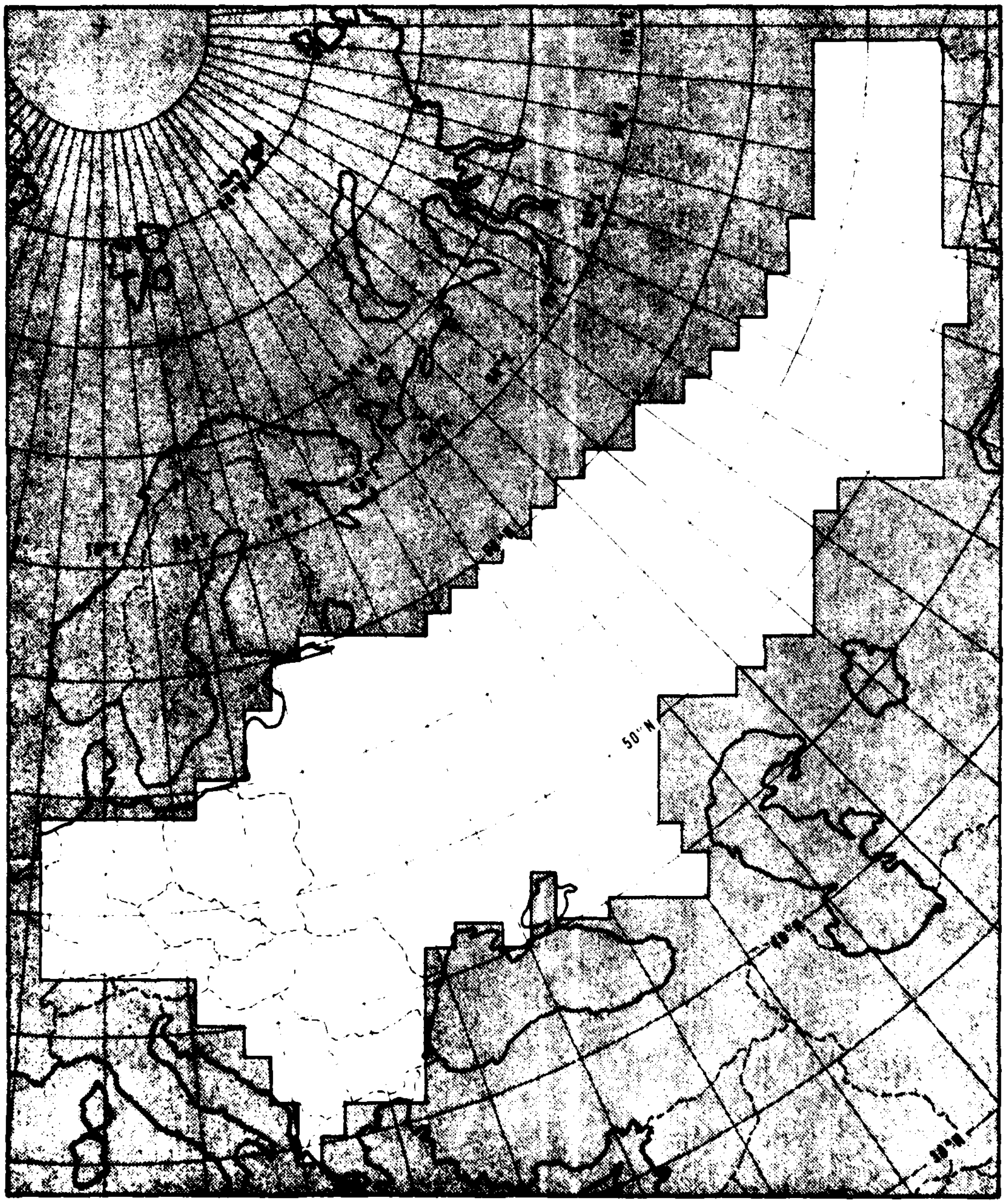

Figure 1-1. Soil Moisture Area 1.

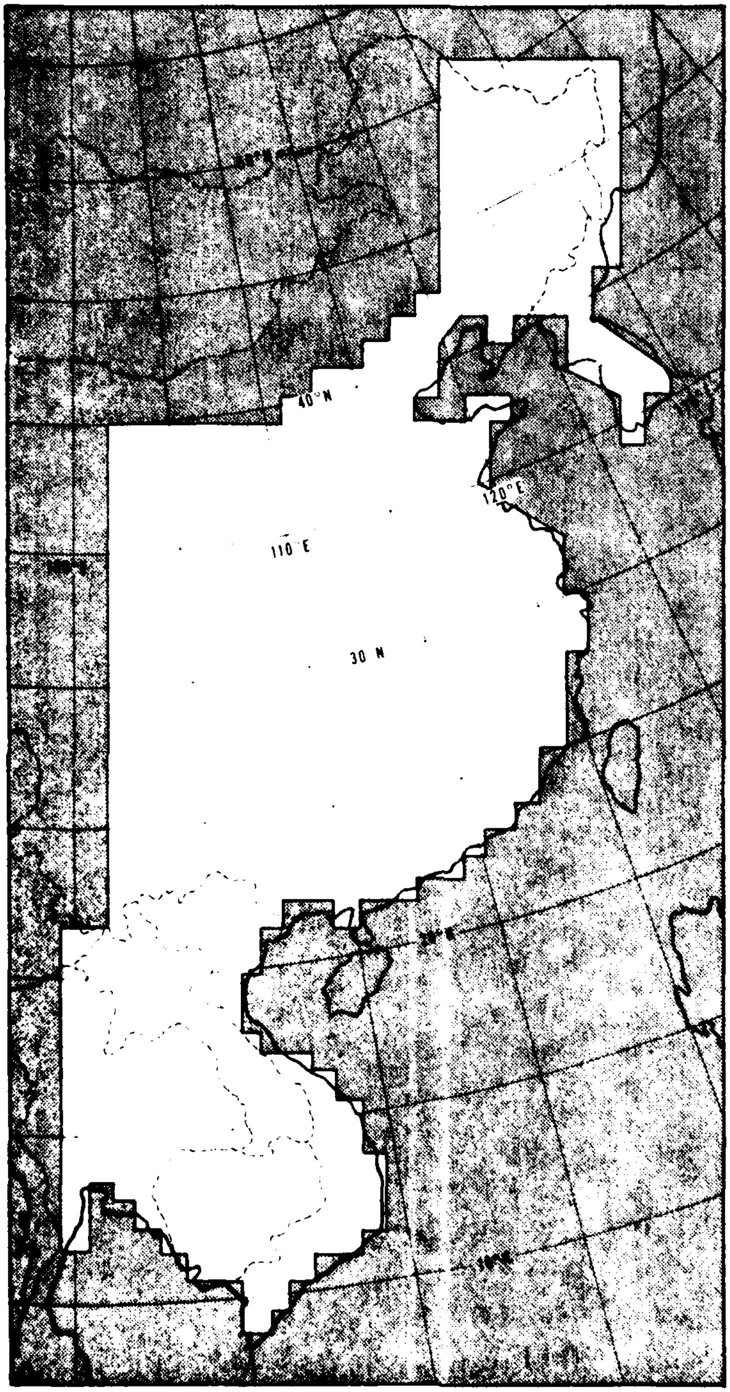

Figure 1-2. Soil Moisture Area 2.

c. Monthly Maps.

(1) Monthly Total Precipitation (mm)

(2) Monthly Mean Temperature (tenths of °C)

(3) Monthly Percent of Mean Precipitation

(4) Monthly Departure from Mean Temperature (tenths of °C)

(5) Ratio: Monthly Actual Evapotranspiration/Potential Evapotranspiration

(6) Accumulated Monthly Total Precipitation since last April (mm)

(7) Accumulated Monthly Total Precipitation since last September (mm)

(8) Percent of Monthly Accumulated Precipitation beginning in April

(9) Percent of Normal Monthly Accumulated Precipitation beginning in September

d. Decade Area Average Tables.

(1) Mean Temperature (tenths of °C)

(2) Total Precipitation (tenths of mm)

(3) Soil Moisture (tenths of mm)

(4) Decade Departure from Long-Term Mean Temperature (tenths of °C)

(5) Percent of Mean Precipitation

(6) Percent of Mean Soil Moisture

e. Monthly Area Average Tables.

(1) Total Monthly Precipitation (tenths of mm)

(2) Monthly Mean Temperature (tenths of °C)

(3) Departure from Mean Monthly Temperature (tenths of °C)

(4) Percent of Mean Monthly Precipitation

(5) Total Precipitation beginning last April (tenths of mm)

(6) Total Precipitation beginning last September (tenths of mm)

(7) Percent of Normal Accumulated Precipitation since last April

(8) Percent of Normal Accumulated Precipitation since last September

The daily temperature and precipitation analyses are normally completed within two days after the data date. The decade and monthly products are normally completed within two days after the last day of the decade period.

1.2 Water Balance, Bookkeeping Method

1.2.1 Water Balance Equation. Soil moisture is calculated as "the balance between the income of water by precipitation and the outflow of water by evapotranspiration (Thornthwaite and Mather, 1957). The bookkeeping method consists of periodically adding rainfall and subtracting evapotranspiration and water surplus to compute a new soil moisture balance. The water balance equation may be written

$$SM = SM_0 + R - ET - PERC - RO \qquad (mm) \qquad (1)$$

where SM = new soil moisture
SM_0 = starting soil moisture
R = rainfall
ET = evapotranspiration
PERC = percolation
RO = runoff

According to Thornthwaite, water in the process of percolation is detained in the soil only briefly. "For instance, in making monthly rather than daily computations it is possible to consider surface runoff and the percolation of gravitational water as one quantity, moisture surplus" (Thornthwaite and Mather, 1955). The water balance equation then reduces to

$$SM = SM_0 + R - ET - S \qquad (mm) \qquad (2)$$

where S = PERC + RO = water surplus.

On the right-hand side of Equation (2), SM_0 is known from previous analysis, R is obtained from surface observations, ET is estimated from potential evapotranspiration using Thornthwaite's equation, and S is any amount in excess of field capacity. SM_0, R, and S are relatively easy to obtain. Estimating ET, however, first requires an estimate of the potential evapotranspiration and is the hydrometeorological heart of Thornthwaite's method.

1.2.2 Thornthwaite's Evapotranspiration Formula. Thornthwaite's empirically derived equation for potential evapotranspiration is

$$PET = D[1.6\ (\frac{10T}{I})^A] \qquad (3)$$

where D = mean duration of daylight (hrs)

T = mean daily temperature for the calculation period (^oC)

I = $\sum_{k=1}^{12} (T_K/5)^{1.54}$ is Thornthwaites heat index (T_K = mean monthly temperature)

A = $0.000000675I^3 - 0.0000771I^2 + 0.01792I + 0.49239$

The value of I for a place is established from climatology, and values of A have been tabulated as a function of I for easy application of the equation. Potential evapotranspiration (PET) in Equation (3) is also called "actual PET" by Thornthwaite to distinguish from "unadjusted PET" (PET before the daylight factor D is applied) which is the quantity in brackets in Equation (3).

The handy thing about Thornthwaite's equation is that, once A, I, and D have been established for a site, the only meteorological element needed is mean daily temperature.

> In refining this formula to achieve more satisfactory results and to utilize only climatic data which are generally available it was possible to eliminate all factors but mean temperature and average length of day. That satisfactory results could be obtained without the use of wind, humidity, or solar radiation seems to be due to the fact that all these important influences on evaporation including temperature vary together (Thorthwaite and Mather, 1955).

Thornthwaite also found that mean daily temperature was the most suitable meteorological variable to use for theoretical reasons.

> In developing a formula which uses climatic factors for computing potential evapotranspiration a conservative climatic parameter must be used; one that will be relatively unaffected by the introduction of conditions of potential evapotranspiration. Atmospheric moisture is very sensitive to an increase of soil moisture necessary for potential evapotranspiration and is thus unsuitable. Maximum and minimum temperatures are also both affected; maximum temperature is not as high over moist soil and minimum temperature is not as low.

Thus diurnal range of temperature is not a conservative property either but would exhibit a reduction if the soil became moist. Since maximum and minimum daily temperatures are affected in the opposite direction by changes in soil moisture, the mean is only slightly affected; mean daily temperature is one of the most conservative climatic elements. Temperature can serve as an index to potential evapotranspiration because there is a fixed relation between the net radiation used for heating and that used for evaporation when conditions exist to achieve the potential rate (Thornthwaite and Mather, 1955).

Once PET has been estimated, an estimate of ET is derived from it for use in the water balance equation. If the soil moisture is at field capacity, ET = PET. However, as the soil dries, additional evapotranspiration takes place at an increasingly lower rate. Thornthwaite's studies indicated that the rate of evapotranspiration is proportional to the amount of water remaining in the soil. For example, if the soil moisture is at one-quarter of field capacity, ET = PET/4.

Thorthwaite's method has been applied in varied regions with varied results. In general, it works best in mid-latitude climates in which it was developed and gives better results when applied over longer time periods (Chang, 1968).

1.3 Soil Moisture Production Programs

1.3.1 Daily Analysis. The surface data for the Soil Moisture temperature and precipitation analyses are collected at AFGWC via the Automated Weather Network (AWN) and sent to USAFETAC each day. At USAFETAC, the observations are put into a station-order sort and saved as part of USAFETAC's climatological data base. The Soil Moisture analysis programs are run immediately after the daily surface sort program. Over 15,000 3-hourly surface synoptic observations for the Soil Moisture areas are received each day. Of these, some 5,500 observations contain maximum/minimum temperature and/or precipitation reports.

The Soil Moisture daily analysis is done in two job steps. The first step extracts temperature and precipitation data, assigns the data to grid points, and removes duplicate reports. The second step analyzes the data over the two Soil Moisture areas. Figure 1-3 shows the daily Soil Moisture production stream.

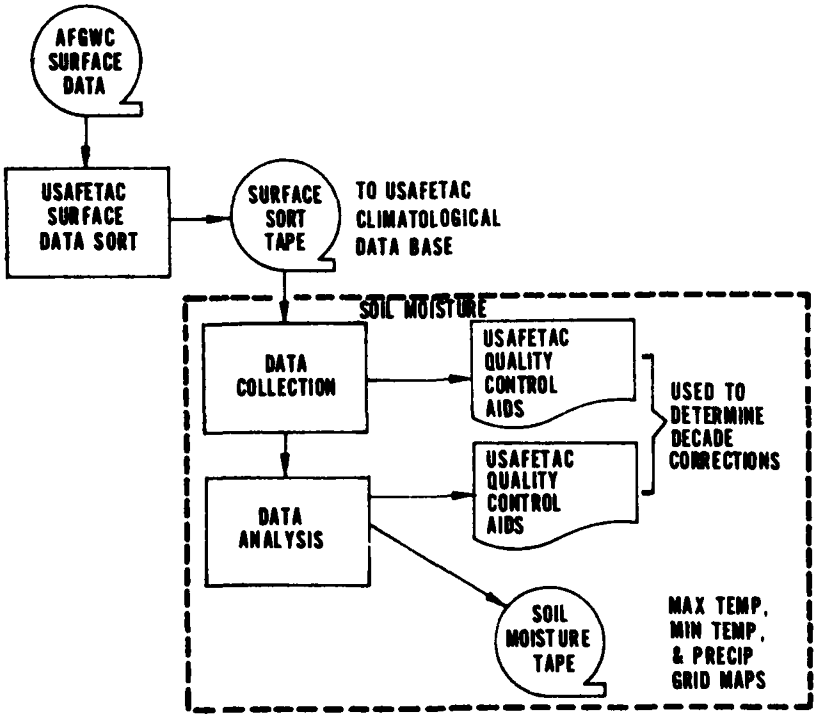

Figure 1-3. Daily Soil Moisture Run Stream.

1.3.2 Analysis Method. The Soil Moisture temperature and precipitation analyses are done using the least-squares surface fitting technique of Mount, et al. (1962). The object of the least-squares method is to minimize the difference between analysis values and actual values. The Soil Moisture program uses the least-squares method to fit a plane surface to the observations around each grid point; the low density of observations over most of the Soil Moisture grid prohibits use of a more complex quadratic surface. The observed-analysis difference to be minimized is:

$$e = \sum_{i=1}^{n} (H_o - H_a)_i^2 \tag{4}$$

where H_o = observed value

H_a = analysis value

A plane through the point H_a is given by

$$H_a = Ax + By + C \tag{5}$$

As each grid point is analyzed, it's coordinates are taken as (0,0) so that C determines the analysis value, H_a (0,0) = C. The x and y coordinates are then taken relative to the analysis point.

e is minimized when

$$\frac{\partial e}{\partial A} = \Sigma\, [x\, (H_o - H_a)] = 0,$$

$$\frac{\partial e}{\partial B} = \Sigma\, [\, y\, (H_o - H_a)] = 0, \text{ and}$$

$$\frac{\partial e}{\partial C} = \Sigma\, (H_o - H_a) = 0 \tag{6}$$

Substituting Equation (5) into Equation (6) and rearranging gives

$$\Sigma H_o x = \Sigma Ax^2 + \Sigma Bxy + \Sigma Cx,$$

$$\Sigma H_o y = \Sigma Axy + \Sigma By^2 + \Sigma Cy, \text{ and}$$

$$\Sigma H_o = \Sigma Ax + \Sigma By + C \cdot N \tag{7}$$

where N is the number of observations.

Applying Cramer's Rule (see, for example, Korn and Korn, 1961) to Equation (7), we get

$$C = H_a\,(0,0) = \frac{\begin{vmatrix} \Sigma x^2 & \Sigma xy & \Sigma H_o x \\ \Sigma xy & \Sigma y^2 & \Sigma H_o y \\ \Sigma x & \Sigma y & \Sigma H_o \end{vmatrix}}{\begin{vmatrix} \Sigma x^2 & \Sigma xy & \Sigma x \\ \Sigma xy & \Sigma y^2 & \Sigma y \\ \Sigma x & \Sigma y & N \end{vmatrix}}$$

$$= \frac{\Sigma x(\Sigma H_o y \Sigma xy - \Sigma H_o x \Sigma y^2) + \Sigma x^2(\Sigma H_o x \Sigma y^2 - \Sigma H_o y \Sigma y) + \Sigma xy(\Sigma H_o x \Sigma y - \Sigma H_o \Sigma xy)}{\Sigma x(\Sigma y \Sigma xy - \Sigma x \Sigma y^2) + \Sigma x^2(N \Sigma y^2 - \Sigma y \Sigma y) + \Sigma xy(\Sigma x \Sigma y - N \Sigma xy)} \tag{8}$$

where C is the analysis value.

At least three observations are needed to uniquely determine a plane through the data. On its first data scan, the Soil Moisture program considers only observations within one grid distance of the analysis point. If there are three or more observations, the least-squares plane value is used. If only two observations are available, a simple mean value is used. If there is only one observation and it is within 1/2-grid distance, that observation value is used. If a value cannot be assigned, the program goes out two grid distances for the precipitation analysis and up to four grid distances for the temperature analyses, searching for three or more observations. If a plane still cannot be determined, the analysis value is filled with a missing indicator.

The daily analyses are quality controlled by USAFETAC analysts. Missing and suspect analysis points are checked using data printouts, nearby reports, and spatial continuity. Corrections to the analyses are made by card input to the Soil Moisture bookkeeping programs. If a value is left missing, the bookkeeping programs insert a mean climatological value.

1.3.3 Soil Moisture Decade Production. The soil moisture bookkeeping parameters are updated three times a month, following the daily processing for the 10th, 20th, and last day of each month, in what is known as the decade run. The decade programs use the daily precipitation and temperature analyses to estimate the terms needed to solve the water balance equation as described in Section 1.2.1. The calculated water balance quantities are used to update the soil moisture bookkeeping from the last decade. The decade run consists of three job steps as shown in Figure 1-4.

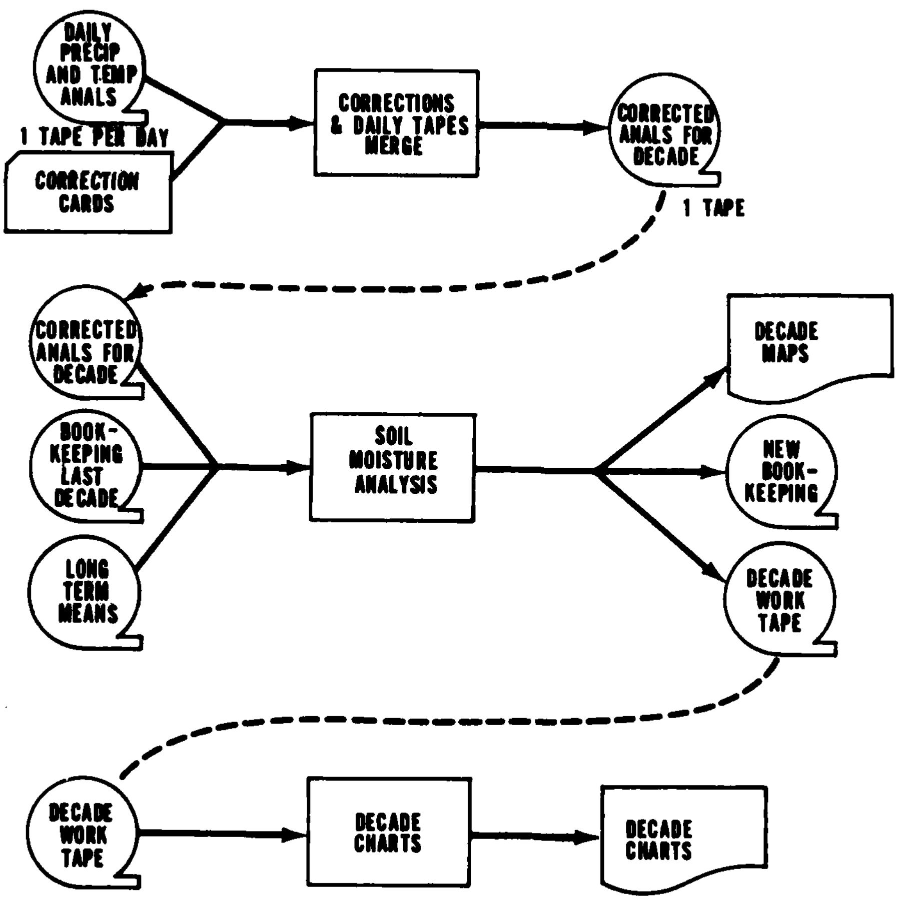

Figure 1-4. Soil Moisture Decade Run.

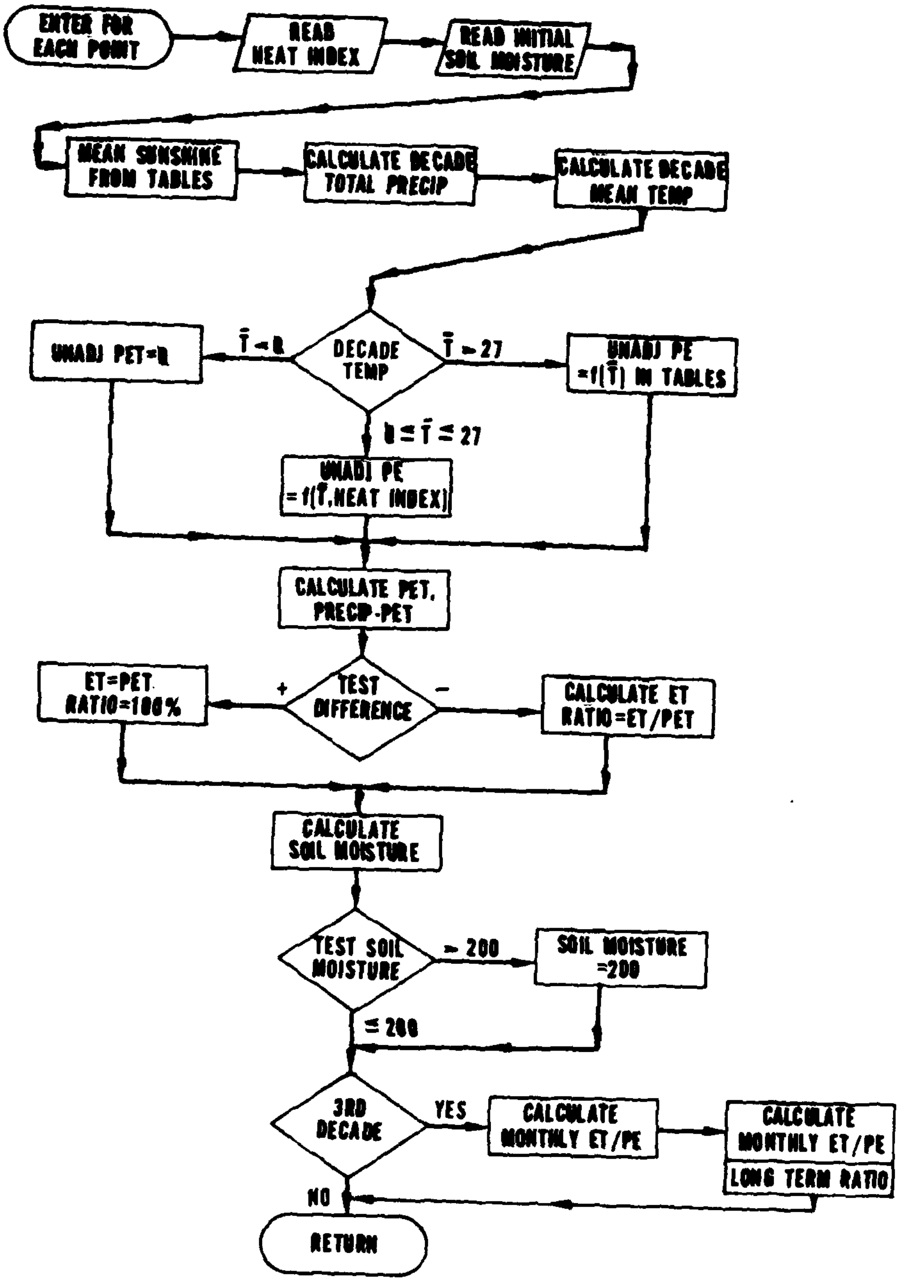

Figure 1-5. Soil Moisture Calculation.

The first decade job merges the daily Soil Moisture tapes and inserts analysis corrections from card input.

The second step does the water balance calculations, updates the bookkeeping parameters, and prints the gridded maps. Figure 1-5 shows the major steps in the soil moisture calculations. Note the Soil Moisture assumption of 200-mm field capacity at all points. Soil moisture values over 200 are set to 200 and the remainder is counted as water surplus.

The third decade job prepares the district averages in tabular form (these are described in Section 1.1) from the updated bookkeeping parameters.

1.4 Summary

The Soil Moisture program is limited by its many simplifying assumptions. These limitations include

a. The Thornthwaite evapotranspiration formula does not consider turbulent transfer or thermal advection. These are important effects on ET, especially on shorter time scales (Thornthwaite and Hare, 1965; Chang, 1968).

b. The assumption of 200-mm field capacity at all points.

c. ET is set to zero if the mean decade temperature is less than 0°C.

d. The data are sparse over some parts of the grid.

e. The bookkeeping inherently assumes that precipitation is spread evenly over the decade period. If most of the precipitation actually occurs early in the decade, actual soil moisture will be less than the calculated value, and vice versa.

These simplifications, of course, make the Soil Moisture program easy to use. Based on Thornthwaite and Mather's (1957) instructions for soil moisture calculations, a major objective of the method was that it required only routinely available surface data as input. These observations do not give the information needed for a more detailed treatment. However, the Thornthwaite method has been found to give good results in many applications. The USAFETAC Soil Moisture program, with it's 10-day time intervals, probably uses as small a time resolution as is feasible. The Soil Moisture program is simple and easy to use, and it has provided useful results for over 20 years.

Chapter 2

AGROMET PROGRAM

2.1 Automated Products

The Agromet program produces daily grid-point values of evaporation from a free water surface (called evapotranspiration potential or ETP in the program), the meteorological elements used to estimate ETP, and a modeled stage of plant growth (phenology). The phenology and analyses of maximum temperature, minimum temperature, precipitation, and snow depth are produced in map form. ETP, net solar radiation, and accumulated daily wind are listed by grid point. Agromet uses the 1/8-mesh AFGWC grid on a polar stereographic projection, which gives approximately 25-NM grid point spacing at 60°N.

The Agromet program covers six geographical areas. Area 1 includes eastern Europe and the central USSR. Area 2 covers China east of 100°E. Area 3 covers the Bay of Bengal region and includes Burma, Bangladesh, and NE India. Area 4 covers NW India, Pakistan, Afghanistan and Iran. Area 5 covers most of the United States. Area 6 covers Europe east from 10°E to the boundary of Area 1. The six Agromet areas are shown in Figure 2-1.

2.2 Methods

2.2.1 The Penman Equation. Penman (1956) combined estimates of the radiation and turbulent diffusion effects on evaporation in a single equation. This was a significant improvement over earlier formulations, such as Thornthwaite's (Section 1.2.2), that modeled energy requirements only. In his development, Penman assumed equality of the coefficients of vapor transfer equations (Penman, 1956; Thornthwaite and Hare, 1965). This assumption allows the transport constants to fall out of the Penman equation

$$ETP = \frac{\Delta R_N + \gamma E_a}{\Delta + \gamma} \qquad \left[\frac{mm}{day}\right] \tag{9}$$

where ETP = evaporation from an open water surface

R_N = net radiation expressed in evaporation units

E_a = aerodynamic component expressed in evaporation units

Δ = $d(e_s)/dT$, the slope of the saturation vapor pressure vs temperature curve

γ = the psychometric constant, ratio of the specific heat of dry air to the latent heat of vaporization of water

The relative importance of the radiation and the aerodynamic effects in Equation (9) is given by the ratio Δ/γ. In the Agroment program, γ is taken as constant at 0.64 (mb/K), although it does vary slightly with temperature and pressure. Δ is calculated from the equation

$$\Delta = \frac{de_s}{dT} = \frac{e_s}{T^2}\left(6790.5-5.02808T+4916.8\times10^{-.0304T}T^2+174209\times10^{-1302.88/T}\right) \tag{10}$$

given on page 372, Smithsonian Meteorological Tables (List, 1951). Δ ranges from 0.44 at 0°C to 3.9 at 40°C. At 7°C, $\Delta = 0.64 = \gamma$, and at 18°C, $\Delta = 2\gamma$. Thus, at typical growing season temperatures, Δ is larger than γ. In addition, R_n is usually larger than E_a, so that the radiation term is usually most important in Equation (9). However, the aerodynamic term shows large short period and local variation (Thornthwaite and Hare, 1965). By including the aerodynamic component, Penman's equation provides more detail than earlier methods and is more complete physically.

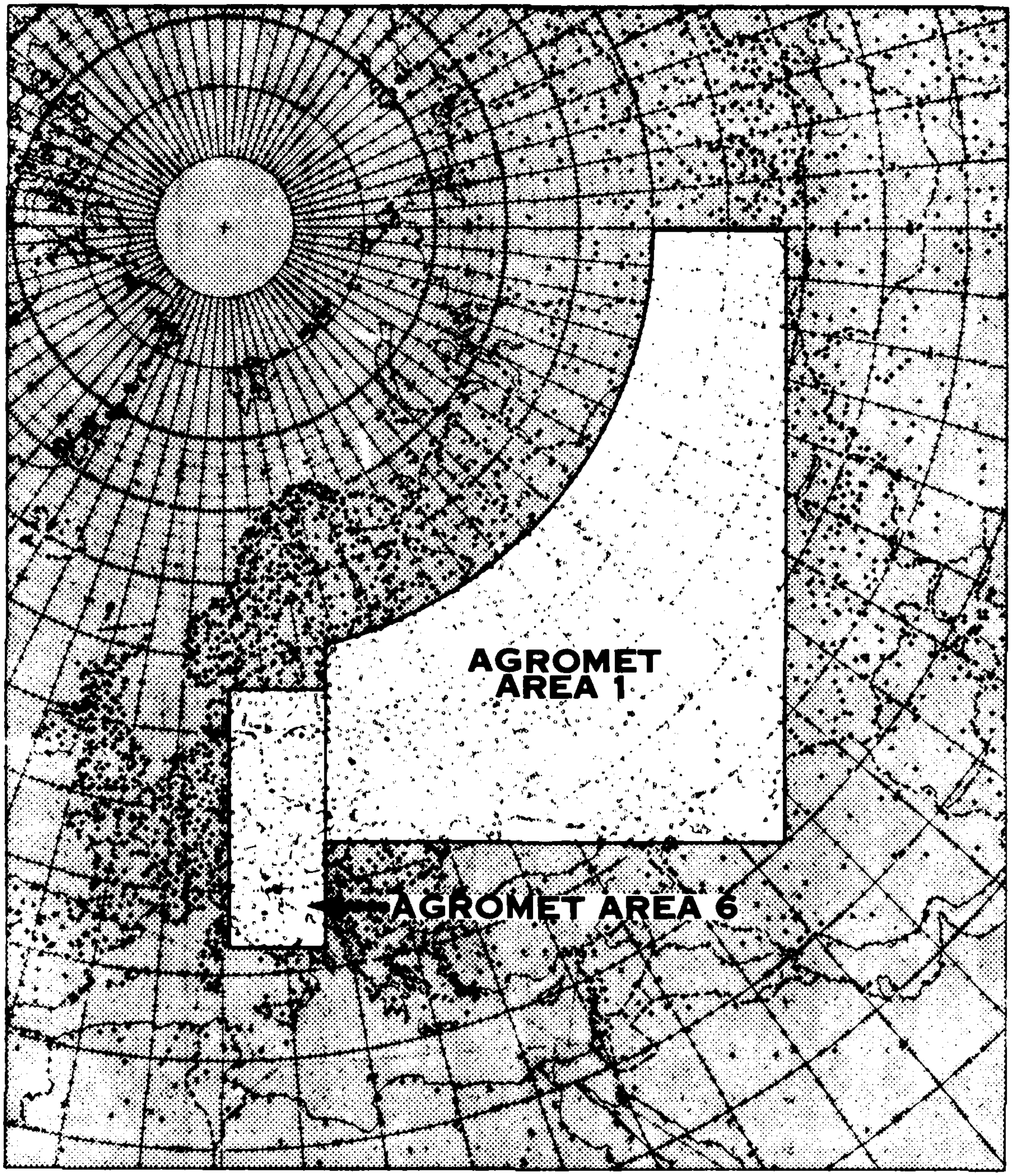

Figure 2-1a. Agromet Areas 1 and 6.

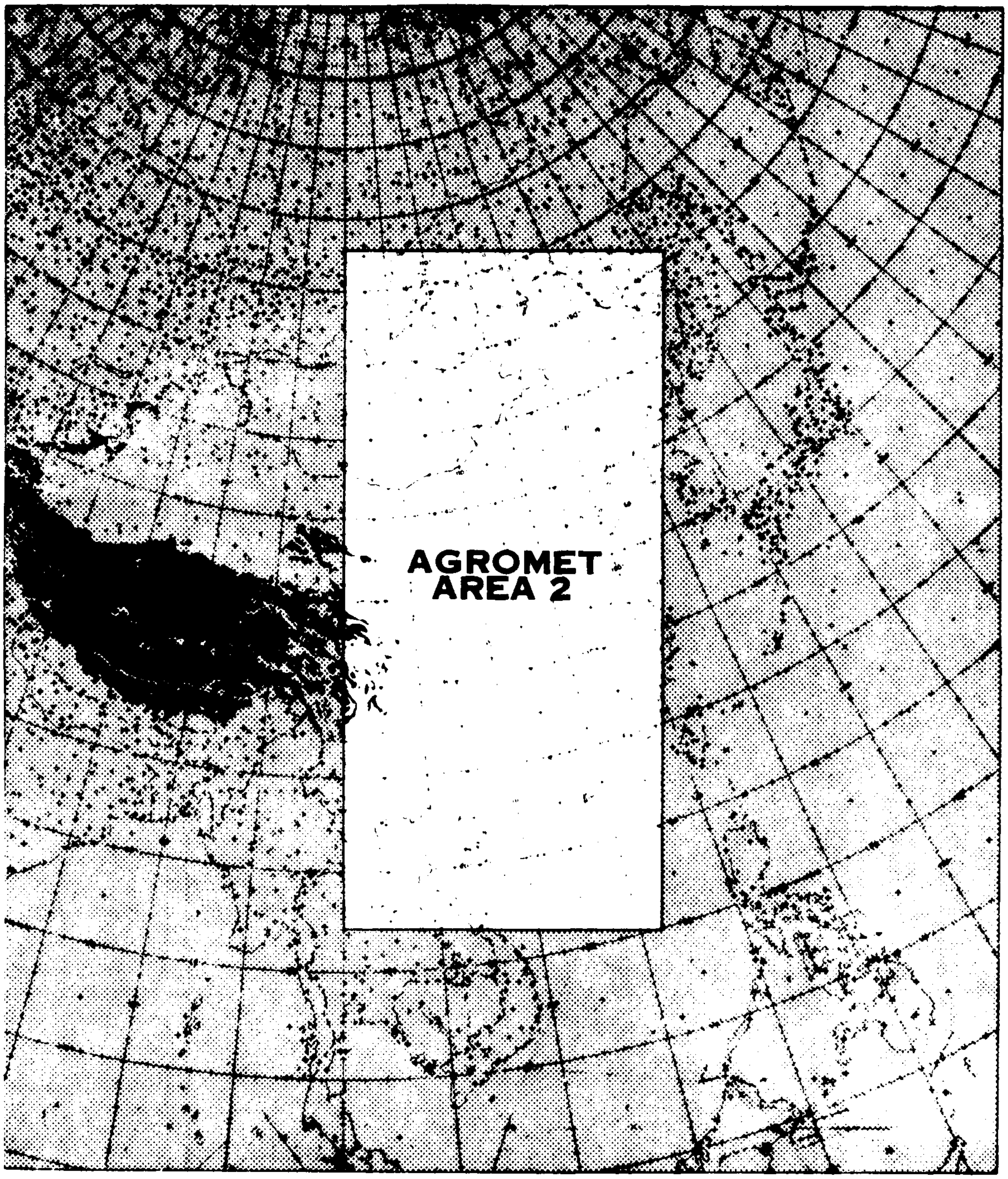

Figure 2-1b. Agromet Area 2.

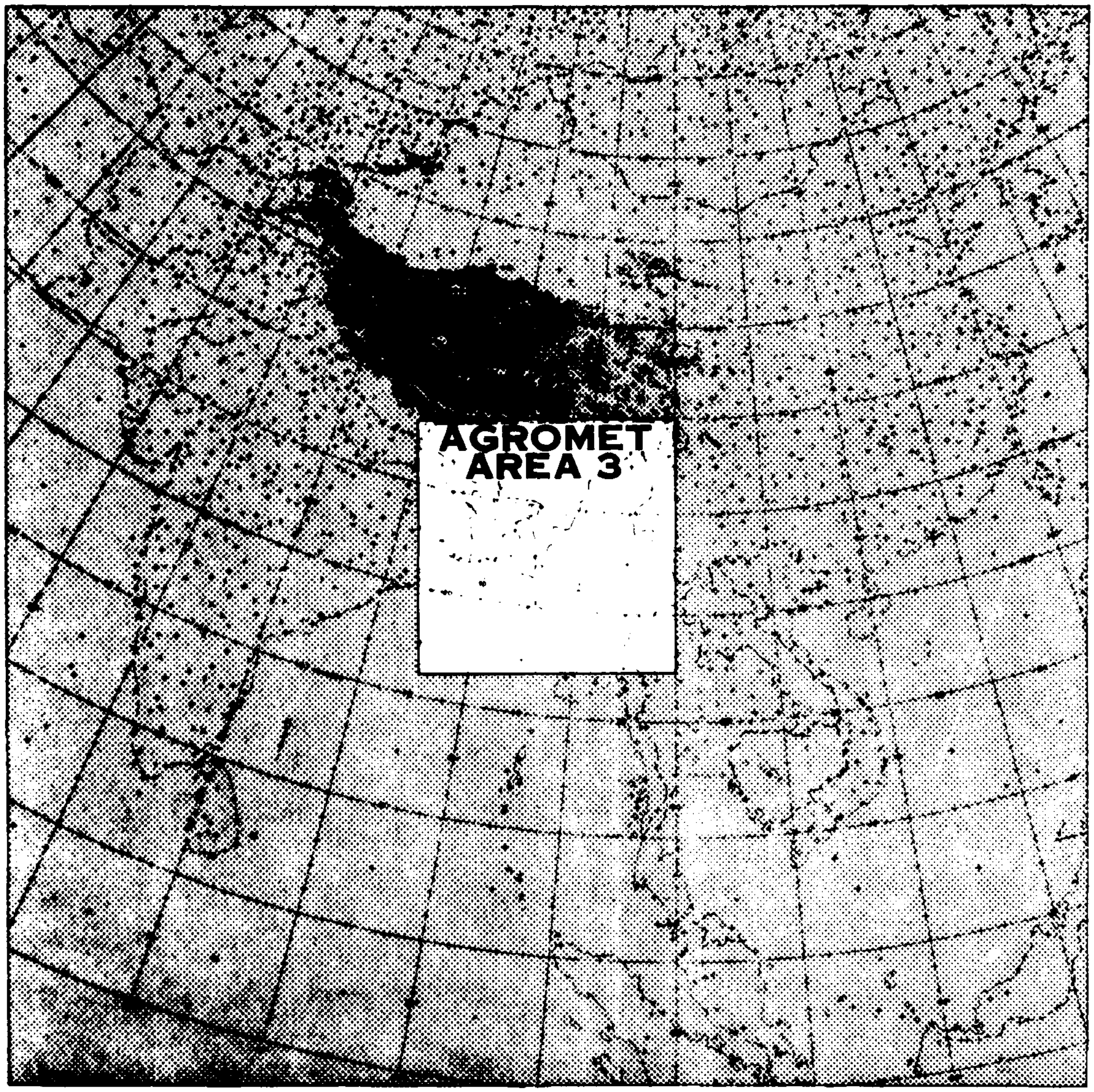

Figure 2-1c. Agromet Area 3.

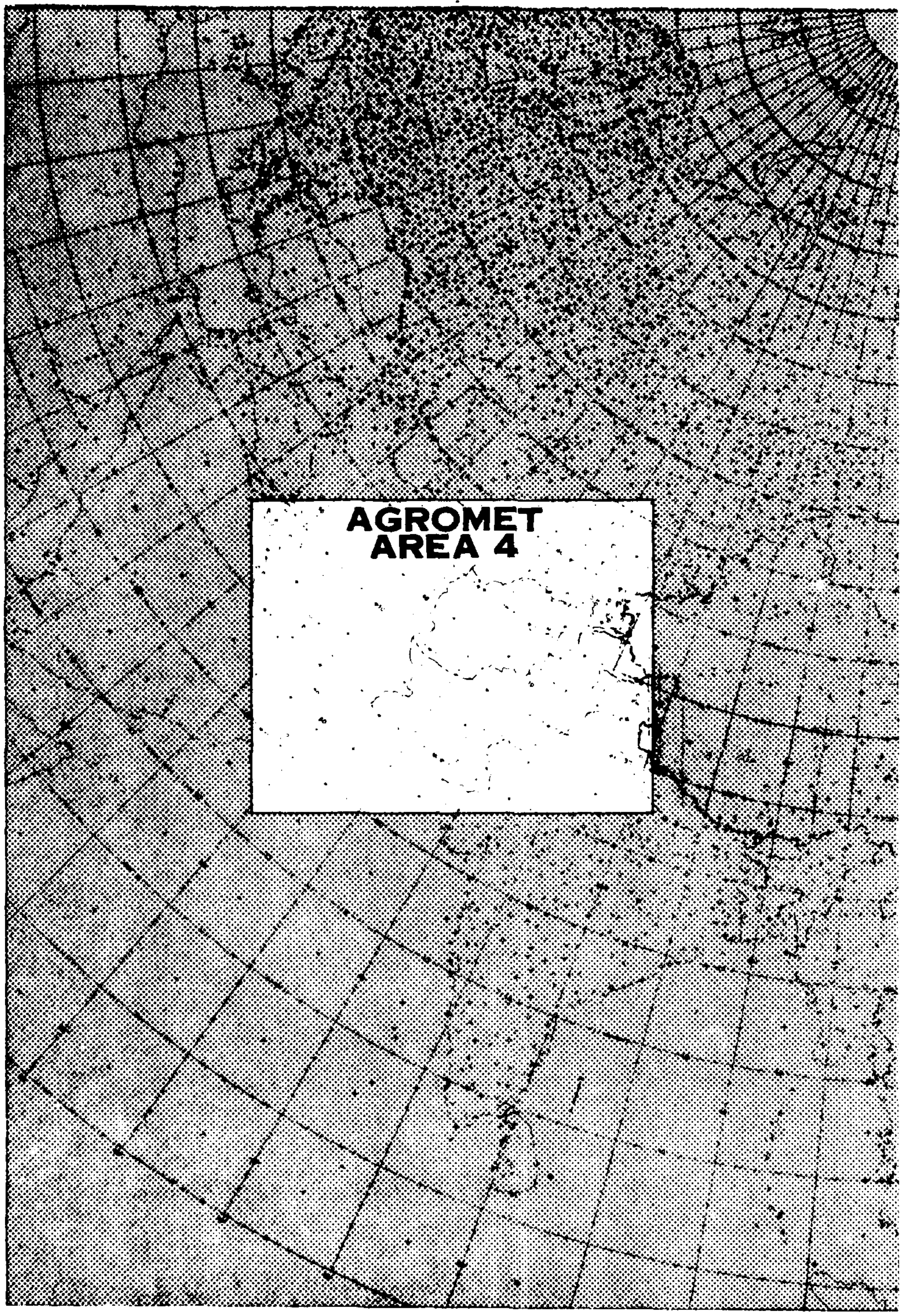

Figure 2-1d. Agromet Area 4.

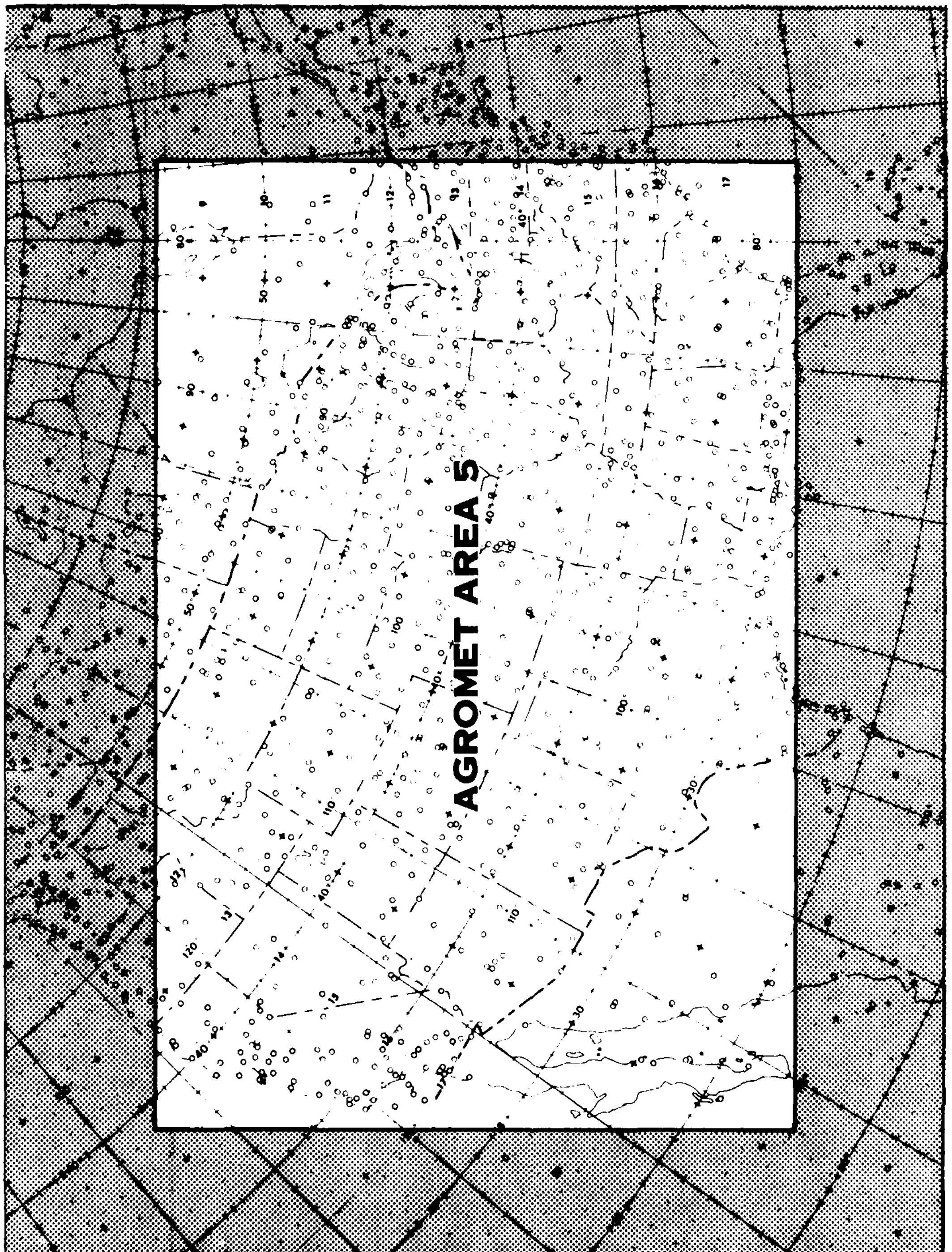

Figure 2-1e. Agromet Area 5.

2.2.2 The Aerodynamic Term. The aerodynamic term in Penman's Equation (9) is calculated using Penman's empirical formula

$$E_a = 0.35 \left(0.5 + \frac{u}{100}\right) (e_s - e) \qquad \left[\frac{mm}{day}\right] \tag{11}$$

where u = cumulative surface wind over a 24-hour period (miles/day)

e_s = saturation vapor pressure (mb)

e = vapor pressure (mb)

Since e and e_s are related to temperature, E_a can be calculated from temperature and wind analyses. The saturation vapor pressure is calculated from the Goff-Gratch formula given on page 350, Smithsonian Meteorological Tables (List, 1951)

$$\begin{aligned} \log_{10} e_s = & -7.90298\,[(T_s/T) - 1] + 5.02808 \log_{10} (T_s/T) \\ & -1.3816 \times 10^{-9} \left(10^{11.334[1 - (T/T_s)]} - 1\right) \\ & +8.1328 \times \left(10^{-3.49149[(T_s/T) - 1]} - 1\right) \\ & + \log_{10} e_{ws} \end{aligned} \tag{12}$$

where T_s = steam point temperature = 373(K)

T = air temperature (K)

e_{ws} = saturation vapor pressure at T_s = 1013(mb)

The vapor pressure, e, also needed in Equation (11), is calculated from Equation (12) using dew-point temperature, T_d, in place of T.

2.2.3 The Radiation Term. The net radiation, R_N, needed in the Penman Equation (9) is estimated by considering the radiation balance

$$R_N = R_S\!\downarrow \; - R_S\!\uparrow \; + R_{NL} \qquad \left[\frac{cal}{cm^2\ min}\right] \tag{13}$$

where $R_S\!\downarrow$ = incoming solar radiation

$R_S\!\uparrow$ = solar radiation reflected at the surface

R_{NL} = net long-wave radiation

The three terms on the right-hand side of Equation (13) are estimated using incoming solar radiation calculations and detailed cloud analyses. The cloud analyses are used to model the incoming solar radiation and net infrared radiation in three-hour steps. Albedo is then estimated as a function of crop stage of growth and used to calculate the reflected solar radiation. These calculations are described in detail below.

a. Direct Beam Solar Radiation. The incoming flux of direct solar radiation under clear skies is calculated from a well-known set of equations (see, for example, Haltiner and Martin, 1957; List, 1951). The basic equation is

$$R^{\downarrow}_{DIRECT} = J_o\, a^{\sec z} \cos z \qquad \left[\frac{cal}{cm^2 min}\right] \tag{14}$$

where J_o = solar constant = 1.94 (cal/cm^{2}min)

a = atmospheric transmissions coefficient for solar radiation

z = zenith distance of the sun

The zenith distance, defined as the angular distance of the sun from directly overhead, is given by

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h$$

where ϕ = latitude

δ = solar declination (latitude at which the sun is overhead)

h = *hour angle (angular distance of rotation from solar noon)*

The transmission coefficient for solar radiation is given by

$$a = 0.73 - 0.077\, u^{0.3} \qquad (15)$$

where u is the precipitable water vapor (cm).

The factor 0.73 is used to account for depletion of solar radiation by dry air, including dust. The term $0.077\, u^{0.3}$ was developed by MacDonald (1960) to account for attenuation of solar radiation by water vapor. The atmospheric water vapor is estimated from the surface vapor pressure using an empirical relationship developed by Idso (1969)

$$\log_{10} u = -0.579 + 0.274 \sqrt{e} \qquad (16)$$

where e is the surface vapor pressure.

From Equations (14), (15), and (16), surface vapor pressure, latitude, time of year (for solar declination), and time of day (for hour angle) are the basic data needed to estimate direct beam solar radiation under clear skies.

b. Diffuse Solar Radiation. Following the procedure given in the Smithsonian Meteorological Tables (List, 1951, p. 420), diffuse solar radiation is calculated as

$$R^{\downarrow}_{DIFFUSE} = \frac{0.91\, R_o - R^{\downarrow}_{DIRECT}}{2} \qquad \left[\frac{cal}{cm^2 min}\right] \qquad (17)$$

where $R_0 = J_0 \cos z$ is the extra-terrestrial incoming solar radiation flux. From Equations (14) and (17), the total solar radiation reaching the surface under clear skies is

$$R^{\downarrow}_{CLEAR} = R^{\downarrow}_{DIRECT} + R^{\downarrow}_{DIFFUSE} \qquad (18)$$

c. Solar Radiation Cloud Factors. The Agromet program uses the AFGWC Automated Cloud Analysis Model (3DNEPH) data at 1/8-mesh grid points (see Fye, 1978) to adjust the clear sky solar radiation for cloudiness. Table 2-1 shows the 15 cloud layers used in the 3DNEPH model. 3DNEPH provides percent cloud cover in each layer, total cloud amount, and low, middle, and high cloud types (Table 2-2).

Table 2-1. 3DNEPH Cloud Layers.

LAYER NO.	LAYER INTERVAL
1	SFC - 150 FT AGL
2	151 - 300 FT AGL
3	301 - 600 FT AGL
4	601 - 1000 FT AGL
5	1001 - 2000 FT AGL
6	2001 - 3500 FT AGL
7	3501 - 5000 FT MSL
8	5001 - 6500 FT MSL
9	6501 - 10000 FT MSL
10	10001 - 14000 FT MSL
11	14001 - 18000 FT MSL
12	18001 - 22000 FT MSL
13	22001 - 26000 FT MSL
14	26001 - 35000 FT MSL
15	35001 - ABOVE FT MSL

Table 2-2. 3DNEPH Cloud Types.

CODE	LOW CLOUD TYPES	MIDDLE CLOUD TYPES	HIGH CLOUD TYPE
0	Type Unknown	Type Unknown	Type Unknown
1	Stratocumulus (SC)	Altocumulus (AC)	Cirrus (CI)
2	Stratus (ST)	Altostratus (AS)	Cirrocumulus (CC)
3	Cumulus (CU)	Nimbostratus (NS)	Cirrostratus (CS)
4	Cumulonimbus (CB)	AC and AS	CI and CC
5	SC and ST	AC and NS	CI and CS
6	SC and CU	AS and NS	CC and CS
7	SC and CB	AC and AS and NS	CI and CC and CS
8	ST and CU		
9	ST and CB		
10	CU and CB		
11	SC and ST and CU		
12	SC and ST and CB		
13	SC and CU and CB		
14	ST and CU and CB		
15	SC and ST and CU and CB		

Agromet reduces 3DNEPH cloud cover to percentage cloud cover in each of three layers: low, middle, and high. A "solar radiation cloud coefficient" (see Smithsonian Meteorological Tables, p. 441 of List, 1951), is associated with each type in each of the three layers (Table 2-3).

Table 2-3. Solar Radiation Cloud Coefficient (K_s) as a Function of Cloud Type.

	Solar Radiation Cloud Coefficient (K_s)		
3DNEPH Cloud Type*	Low Cloud	Middle Cloud	High Cloud
0	1.0	1.0	1.0
1	0.34	0.51	0.82
2	0.25	0.41	0.82
3	0.34	0.17	0.82
4	0.12	0.46	0.82
5	0.30	0.30	0.82
6	0.34	0.25	0.82
7	0.20	0.35	0.82
8	0.30	1.0	1.0
9	0.18	1.0	1.0
10	0.20	1.0	1.0
11	0.32	1.0	1.0
12	0.22	1.0	1.0
13	0.24	1.0	1.0
14	0.22	1.0	1.0
15	0.26	1.0	1.0

*See Table 2-2.

Using these cloud coefficients and the low, middle, high cloud amounts calculated from the 3DNEPH, a cloud solar radiation depletion factor is calculated

$$F_s = \prod_{i=1}^{3} [1 - C_i(1 - K_{s_i})] \qquad (19)$$

where C_i = the cloud amount

i = 1, 2, 3 for low, middle, and high cloud

K_s = the solar radiation cloud coefficient for the cloud type reported by 3DNEPH in layer i

F_s = the fraction of the incoming solar radiation depleted due to cloud cover

Combining Equations (18) and (19), the incoming solar radiation is given by

$$R_S\downarrow = F_S \, R_{S_{CLEAR}}^{\downarrow} \qquad [\frac{cal}{cm^2 min}] \qquad (20)$$

d. Reflected Solar Radiation. Solar radiation reflected at the surface is given by

$$R_S\uparrow = -A \, R_S\downarrow \qquad [\frac{cal}{cm^2 min}] \qquad (21)$$

where A is the albedo.

In the Agromet program, the albedo is specified as a function of the modeled stage of crop growth (phenology). The relationship is shown in Table 2-4.

Table 2-4. Richardson's Relationshop for Albedo as a Function of Phenology.

Phenology	(1 - A)
$-3.0 \leq P \leq 0.99$	0.90
$1.0 \leq P \leq 1.99$	0.90 - 0.14 (P - 1.0)
$2.0 \leq P \leq 3.99$	0.76
$4.0 \leq P \leq 5.99$	0.76 + 0.14 (P - 4.0)
$6.0 \leq P \leq 6.99$	0.90

Combining Equations (20) and (21), the net solar radiation is

$$R_{NS} = R_S\downarrow + R_S\uparrow = (1-A) \, R_S\downarrow \qquad [\frac{cal}{cm^2 min}] \qquad (22)$$

e. Long-Wave Radiation. The net long-wave radiation is calculated following Geiger (1965). For clear skies

$$R_{NL_{CLEAR}} = \sigma \, T^4 \, (0.18+0.25X10^{-0.126e})-0.007(T-T_g) \; [\frac{cal}{cm^2 min}] \qquad (23)$$

where σ = Stephan-Boltzmann constant

T = air temperature (K)

T_g = ground temperature (K)

e = vapor pressure (mm Hg)

In the Agromet program, $T = T_g$ is assumed, and e is in mb. Equation (23) reduces to

$$R_{NL_{CLEAR}} = \sigma \, T^4 (0.18 + 0.25 \times 10^{-0.0945e}) \qquad [\frac{cal}{cm^2 min}] \qquad (24)$$

The effects of clouds are accounted for by a long-wave radiation cloud factor, F_L (Geiger, 1965). The method used to get F_L is similar to that used for the cloud solar radiation depletion factor (Section 2.2.3c). Individual long-wave cloud coefficients (K_L) are associated with the cloud type in each of the low, middle, and high cloud layers (Table 2-5). F_L is calculated by

$$F_L = \{\sum_{i=1}^{3} [C_i \sqrt{K_{Li}} \prod_{j=o}^{i-1} (1 - C_j)]\}^2 \tag{25}$$

where C_i = cloud amount in layer i (C_0 = 0 by definition)

K_{Li} = K_L for the cloud type in layer i

Table 2-5. Long-Wave Cloud Coefficient (K_L) as a Function of Cloud Type (3DNEPH).

3DNEPH Code	Long-Wave Coefficient (K_L)		
All Types	C_L	C_M	C_H
0	0	0	0
1	0.20	0.17	0.04
2	0.24	0.20	0.06
3	0.20	0.24	0.08
4	0.24	0.19	0.06
5	0.22	0.21	0.06
6	0.20	0.21	0.06
7	0.22	0.21	0.06
8	0.22	0	0
9	0.24	0	0
10	0.22	0	0
11	0.22	0	0
12	0.22	0	0
13	0.22	0	0
14	0.22	0	0
15	0.22	0	0

The net long-wave radiation, including cloud effects, is then given by

$$R_{NL} = R_{NL_{CLEAR}} - F_L(\sigma T^4 - R_{NL_{CLEAR}}) \quad [\frac{cal}{cm^2 min}] \tag{26}$$

2.2.4 Agromet ETP Calculation. With the estimates of the three radiation components, $R\uparrow$, $R\downarrow$, and R_{NL}, and of the aerodynamic term, E_a, the evapotranspiration potential may be calculated from the Penman Equation (9). In practice, the evapotranspiration from the incoming solar radiation, ETP1, and that from long-wave radiation and the aerodynamic term, ETP2, are calaculated seperately at AFGWC for each grid point. At USAFETAC, the temperature and precipitation analyses are used to run the plant phenology model, and albedo is estimated as a function of plant phenology. ETP is then calculated from ETP1, ETP2, and albedo.

The form of the Penman equation used by Agromet is developed from substituting Equation (13) into Equation (9)

$$ETP = \frac{\Delta\ (R_s\uparrow + R_s\downarrow)}{\Delta + \gamma} + \frac{\Delta\ R_{NL} + \gamma\ E_a}{\Delta + \gamma} \tag{27}$$

Then, substituting from Equation (21)

$$ETP = (1 - A)\ \frac{\Delta\ R_s\downarrow}{\Delta + \gamma} + \frac{\Delta\ R_{NL} + \gamma\ E_a}{\Delta + \gamma} \tag{28}$$

And, by definition of ETP1 + ETP2

$$ETP = (1 - A)\ ETP1 + ETP2 \tag{29}$$

2.3 Agromet Production System

2.3.1 AFGWC Agromet. The AFGWC Agromet production system runs eight times a day, following the processing of 3-hourly (00z plus every 3 hours) 3DNEPH cloud analysis model (Fye, 1978) and surface observations. The 00Z through 18Z Agromet runs consist of three job steps: a surface analysis, a first guess for daily maximum and minimum temperature, and a summation of the Penman equation parameters and estimated precipitation. In addition to these three steps, the 21Z run produces the final daily temperature and precipitation analyses and the daily Agromet data tape. Figure 2-2 shows the AFGWC production. The individual programs are discussed briefly in the following sections.

a. Surface Analysis. The first program to run in each 3-hourly Agromet cycle is the surface analysis. This program provides a 1/4-mesh grid point analysis of surface temperature, dew-point depression, and u and v wind components.

These analyses are done over an expanded area which extends one full mesh grid distance beyond the boundaries of each Agromet area. This procedure excludes possible boundary problems from the stored analysis fields.

The surface temperature and dew-point depression analyses use the Barnes (1964) technique with three scans. The u and v wind components are derived from 1000-mb D-values. The D-values, in turn, are derived from a Barnes analysis of surface temperature and pressure. The latest available coarse mesh analysis (dew point) and forecast (temperature and pressure) from the AFGWC data base are used as first guess for these analyses. These analyses are stored in the 1/4-mesh analysis data base which is created by Agromet.

b. Maximum and Minimum Temperature First Guess. This program stores daily maximum and minimum temperatures from the AFGWC 1/2-mesh hemispheric surface temperature analysis. Every 3 hours, the 1/2-mesh analysis is interpolated to 1/4 mesh and the value at each grid point compared to the maximum and minimum values found thus far in the day. If the latest temperature exceeds the previous maximum or minimum, the new extreme replaces the previous value. The resulting fields are stored in the 1/4-mesh data base and are used as first guess by the 21Z cycle maximum/minimum temperature analysis.

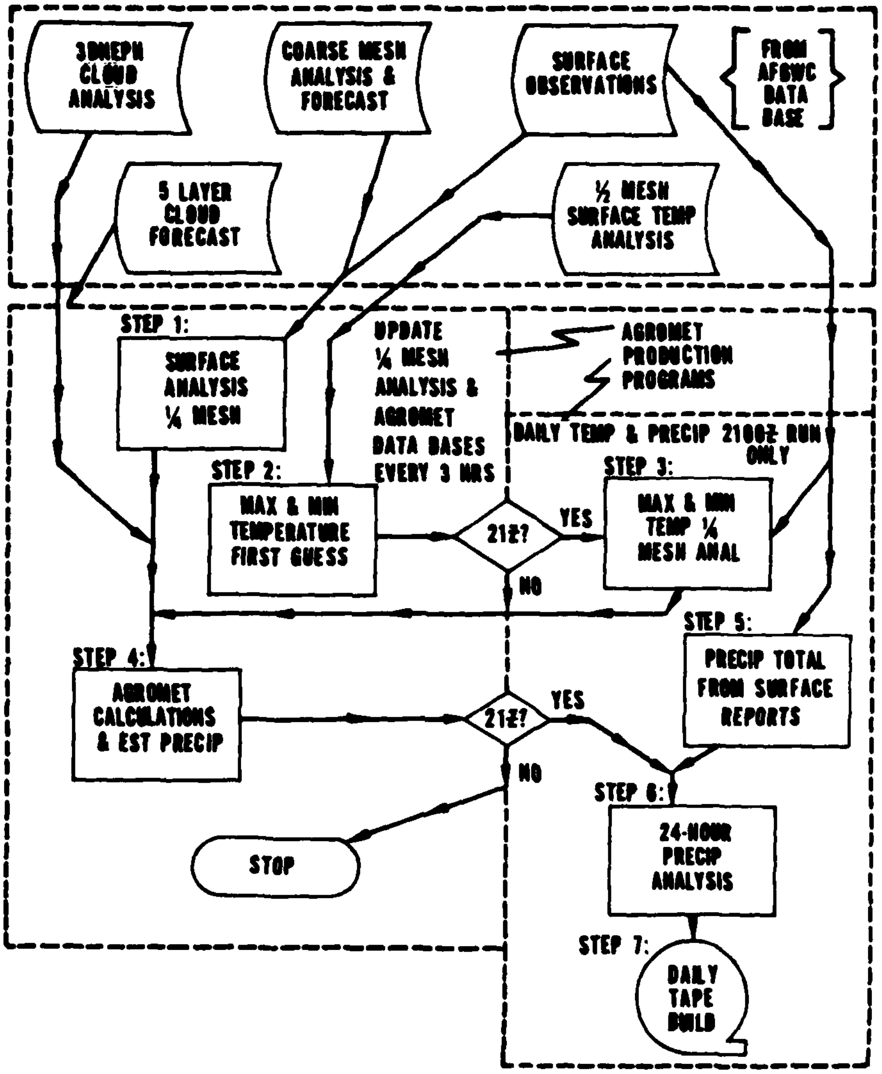

Figure 2-2. AFGWC Daily Agromet Production.

c. ETP Calculations and Estimated Precipitation. This program calculates the evapotranspiration (ETP) parameters (see Section 2.2) and estimated precipitation every 3 hours. The ETP parameters are calculated using the temperature, dew-point depression, and surface wind components stored in the 1/4-mesh data base and the AFGWC 3DNEPH model data base. Solar radiation reaching the surface is computed at each grid point by positioning the sun at its location 1-1/2 hours before data time and moving it across the sky in 1/2-hour increments to its position 1-1/2 hours after data time. Daily values of the ETP parameters thus represent the period from 2230Z of the previous day through 2230Z on the data date. The ETP parameters are summed every 3 hours and stored in the Agromet data base.

An estimated precipitation value is calculated for each grid point every 3 hours based on the cloud type and amount from the 3DNEPH data base using a method suggested by Follansbee (1973). The estimated precipitation is accumulated at each grid point through the data day.

Three-hour quantitative precipitation forecast (QPF) values are also stored at each grid point. The QPF values are from the AFGWC 5-layer, 1/2-mesh cloud forecast model. The 1/2-mesh QPF field is interpolated to 1/8-mesh and the sum of the QPF values at each grid point is accumulated during each Agromet run and stored in the Agromet data base.

d. Maximum and Minimum Temperature 1/4-Mesh Analysis. The Agromet maximum and minimum daily temperature analysis is done on the 21Z run. Using maximum and minimum temperature reports from surface observations, the program does a Barnes (1964) analysis with three scans for both fields. The first guess fields are supplied from the 3-hourly Agromet runs (see Section 2.3.1b). These analyses are stored in the 1/4-mesh analysis data base.

e. Precipitation Total from Surface Reports. This program assigns precipitation reports from surface observations to the nearest 1/8-mesh grid point to the reporting station. Two values are accumulated, precipitation amounts as reported and "bogus" precipitation values. The bogus precipitation values are estimates of precipitation based on the weather types reported in the observation. These values are stored by the AFGWC data base building programs in a reserved part of the surface observations. Agromet uses the accumulated reported values if they are greater than 5 mm. Otherwise, it uses the greater of the two values. The program also checks for convective precipitation and spreads one-half of the daily accumulation to immediately adjacent grid points if no other precipitation is reported for those grid points. The resulting analysis is stored in the Agromet data base.

f. 24-Hour Precipitation Analysis. This program spreads the precipitation totals accumulated from surface observation to surrounding grid points with no reports. The spread is based on the precipitation amounts estimated from the 3DNEPH cloud analysis. An estimated precipitation amount is available at each grid point. For points that also have reported precipitation amounts, the ratio Reported Amount/Estimated Amount (R/E) is calculated. The (R/E) values are then spread using a linear distance weighted scheme. Each grid point then has an (R/E) value or a spread value, (R/E)s associated with it. Reported precipitation is used for all points where available. For points with no reported precipitation, the (R/E)s is used to determine a value. If the (R/E)s is less than 10, precipitation is (R/E)s times the estimated value from the 3DNEPH; otherwise the QPF value is used for the grid point. Normally, less than 12 QPF values are used in any Agromet area. The precipitation analysis scheme is shown in Figure 2-3.

g. Agromet Tape Build. The daily Agromet data tape is produced on the 21Z cycle. The program performs gross error checks on the final values and checks the tapes for proper format. Finally, the program resets all Agromet data base fields to zero for the start of the next day's run.

2.3.2 USAFETAC Programs. Agromet processing at USAFETAC starts with the receipt of the daily Agromet data tape from AFGWC. The tape is checked shortly after transmission to ensure that all data records are in the right format, that all characters are valid, and that the temperature and precipitation fields are filled. The check program also reformats the data for processing on USAFETAC's IBM 4341 computer. Once a tape has been received and checked, the daily Agromet production is scheduled.

The daily Agromet production at USAFETAC consists of four steps, shown in Figure 2-4. First, grid-point maps of maximum temperature, minimum temperature, precipitation, and snow depth are prepared and written to tape and hard copy. The second step updates the crop phenology model based on the meteorological parameters. Third, albedo is computed based on the phenology, and the albedo is used to compute net solar radiation and ETP. These first three steps are repeated for each Agromet area. A separate file is written to the output tape for each of the six areas. The fourth step of the Agromet production copies observations from the USAFETAC surface observation file onto the courier tape. The final output is then a seven-file data tape for transmission to Agromet customers.

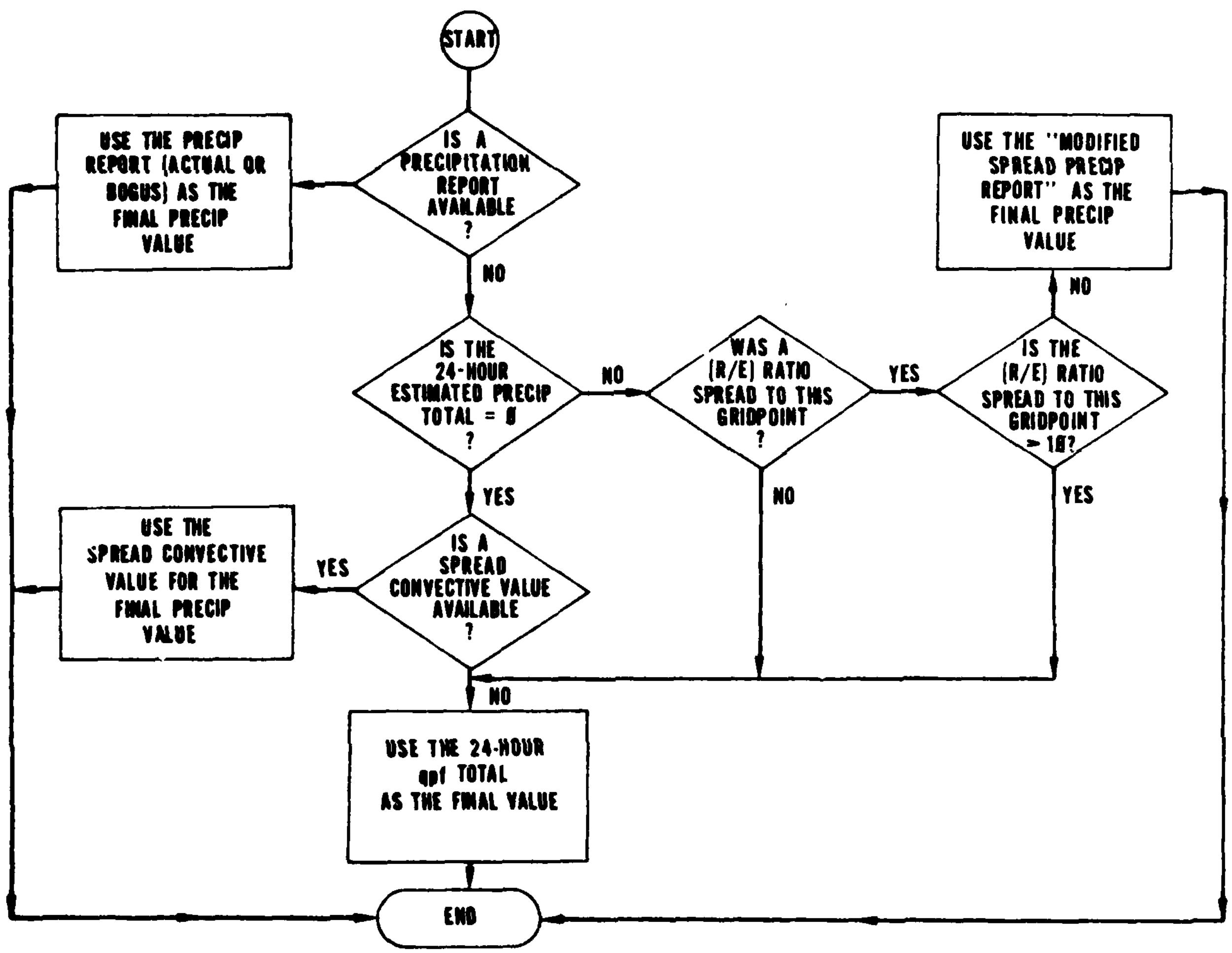

Figure 2-3. Precipitation Analysis Scheme.

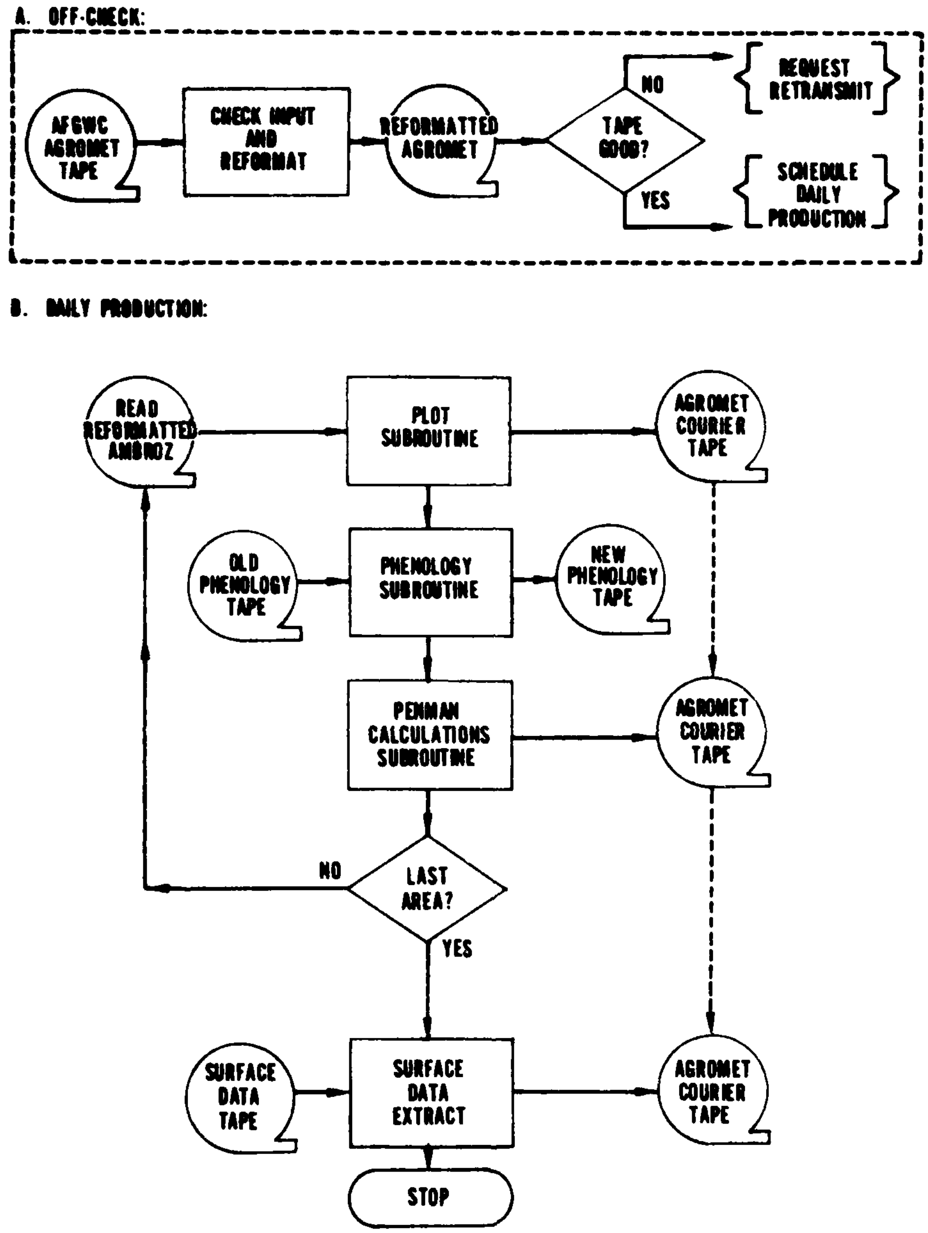

Figure 2-4. USAFETAC Agromet Production.

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GLOSSARY OF SOIL MOISTURE TERMS

a. Soil Moisture. The amount of water, measured as depth over an area, retained against gravity in the root zone of the soil. The root zone is the depth of soil from the surface to the bottom, or just below the plant roots. Soil moisture depends on moisture availability, soil type, vegetation type, and plant stage of growth.

b. Field Capacity. The maximum amount of soil moisture. Field capacity varies from a few millimeters in shallow sand to well over 400 mm in a deep silt loam.

c. Water Surplus. Water in excess of field capacity. This water cannot be retained and is in the process of runoff, percolation, or evaporation.

d. Runoff. Water discharged from an area through stream channels.

e. Percolation. The gravitational pull of water from the root zone into ground water.

f. Evapotranspiration. The combined process of evaporation from the surface and transpiration of water through plant leaves. The term is also used to denote the amount of water loss from the soil to the air by the evapotranspiration process. Evapotranspiration depends on the evaporative demand of the air, moisture availability, soil type, and vegetation.

g. Potential Evapotranspiration. The amount of water lost from the soil by evapotranspiration from the surface completely covered by vegetation with an abundant water supply at all times. Thornthwaite (1944) developed the concept of potential evapotranspiration to provide a measure of the water need of a region. Besides complete crop cover and soil mosture at field capacity, "the size of the area under the high moisture conditions has to be large enough, so that evapotranspiration from the area is not affected by external factors such as the advection of moist or dry air masses and their modification by local conditions" (Thornthwaite and Mather, 1955). Potential evapotranspiration is the maximum rate of evapotranspiration given the meteorological conditions and is a function of meteorological elements only.

h. Moisture Deficit. The difference between actual evapotranspiration and potential evapotranspiration. A positive moisture deficit indicates the amount by which soil moisture is unable to support evapotranspiration at the potential rate.

LIST OF ABBREVIATIONS AND ACRONYMS

AFGWC	Air Force Global Weather Central
AWN	Automated Weather Network
ETP	Evapotranspiration Potential
NM	Nautical Mile
PET	Potential Evapotranspiration
QPF	Quantitative Precipitation Forecast
R/E	Spread Ratio
USAFETAC	United States Air Force Environmental Technical Applications Center
3DNEPH	3-Dimensional Nephanalysis (AFGWC Automated Cloud Analysis Model)